Research in Unsteady and Nonequilibrium
Supersonic Gas Dynamics

Progress Report

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Summary

This semi-annual progress report reviews our beginning efforts in a projected three-year NASA supported study of unsteady and nonequilibrium flow in supersonic gas dynamics. Experiments on reflected shock-wave interactions with turbulent thick boundary layers have shown a pressure defect across the thick boundary layer which increases with increasing Mach Numbers. A Reynold's number sensitivity in these phenomena has also been determined. Construction and design for our other proposed studies related specifically to Ludwieg-Tube phenomena are proceeding according to schedule.

Introduction

This semi-annual report reviews our beginning efforts in a projected three year NASA supported study of unsteady and nonequilibrium flow in supersonic gas dynamics. In this first stage, the shock tube set-up has begun and various equipment and supplies have been acquired in the construction of the diagnostics planned for our experiments.

Professor Joseph A. Johnson III, Principal Investigator, has worked one half time on this research during the reporting period. At various times, Mr. Donald Young, Mr. Airfeil Ashley, and Miss Yvonne Brown, Southern University physics majors, have participated in this research. Dr. James Turner joined the Southern University faculty as Assistant Professor of Physics on June 8, 1971 and has participated one-half time in these efforts since then. Mrs. Eloise W. Young, Secretary, and Miss Dorothea Grimes, student worker, Department of Physics have provided all necessary typing and secretarial services. In addition, several useful consultations were held with Professors Carl Spight and Wesley Harris of our department concerning theoretical aspects of our experiments. All personnel costs in this stage of our research are being borned by Southern University.

Visits by the Principal Investigator to the NASA Marshall Space Flight Center, Huntsville, Alabama and to the NASA Manned Space Flight Center, Houston, Texas have proven useful to our efforts. Consultations with various equipment manufacturers and with several faculty members at Yale University and at the Massachusetts Institute of Technology have also been beneficial. Furthermore, previously unavailable resource materials have been purchased, using the funds from this NASA contract, pursuant to the objectives of our studies.

Specifically, we have continued our investigations into reflected shock-wave turbulent boundary layer interactions for thick boundary layer pipe flow. These efforts, which have been reported in part in reference 1, are the first phases of our general investigations into the interactions of supersonic flow and shock-waves with non-equilibrium phenomena. The continuing phases will include the experiments on supersonic relaxing flow in the wake of a thin stem as discussed in reference 2. In addition, we have begun construction on the low pressure 5.08 cm (2") diameter section of the Ludwieg-Tube; this will serve in the meantime as a conventional shock-tube for some preliminary investigations in unsteady supersonic flow in the contact region (see reference 3). Shadow-graph and schleren photography along with pulsed laser and photo-electric interferometry are being developed for use in these investigations.

Scope and Results of Work Performed

The motivation and background for our present investigations are given in Reference 2. Insofar as this present report is concerned, we have focused on our continuing interest in relaxing and nonequilibrium gaseous phenomena. That is, the programs which are detailed in Reference 2 indicate a desire to look at unsteady supersonic nozzle flow for a relaxing gas. Consistent with this, we have already begun to study the propagation of (reflected) shock waves into a region heavily impregnated with turbulent boundary layer flow. The extension of these studies to cases of interest involving relaxing gases is eagerly anticipated. This progress report will give the present status of these data.

The Experimental Configurations

The experimental set-up has proceeded through the construction of sections G, F, and E of the tube illustrated in Figure 1. Two inch nominal diameter schedule 80S stainless steel seamless pipe and 600 lb. forged steel flanges are being used so as to ensure adequate pressure handling strength for the high pressure experiments. Schleren and shadowgraph flash photography using a 35 mm polaroid camera with a 200 mm lens system and a 40 ns wide 50 Kw pulsed lamp has been provided for these studies. The set-up for C-W photoelectric and pulsed laser interferometry is also in progress. Figure 2 shows this, along with associated diagnostics in an overview of the entire laboratory.

In addition, our shock-tube for reflected shock-wave studies has been set-up as shown in Figure 3. Two inch diamter galvanized steel threaded pipe is being used with two inch standard couplings. The inner threads on the couplings provide the roughened surface for inducing turbulence in the thick boundary layer. The driver tube length is 1.52 m (5') and there is a 3.66 m (12') driven tube segment between the test section and the diaphragm. This is to insure a test period of duration sufficient for the observation of reflected shock-wave interactions without interference from the contact surface or the reflected expansion wave. Two high speed pressure transducers provide pressure measurements for the primary and reflected shock waves. Further, these gauges signal the passage of the shock waves by fast pulses from which shock wave velocities can be determined using the precision counters indicated.

Data

No shock waves have been produced in the configuration whose design is shown in Figure 1 since this set-up is still incomplete. However, static schlieren photographs have been taken with the optical components properly placed. These confirm that the magnification of the 2.54 cm (1") field is adequate to fill the field of view of the 35 mm polaroid camera. Further tests have been performed using the flash tube and the photomultiplier in order to confirm that the triggering jitter on an external firing pulse meets specifications and that the light output is sufficient for 35 mm photography with adequate depth of field. Similar confirmations of selected specifications have been obtained for the pulsed Q-switched laser. Some of these results are indicated in Figure 4.

Useful data are being obtained in our experiments with reflected shock waves. We have measured primary shock wave velocities (W_s) and reflected shock wave velocities (W_r) by measuring the time required for the shock waves to pass between the pressure transducers of known separation. We have also measured the pressure ratio across the reflected shock wave (P_5/P_2) using these same transducers. As a run-diagnostic, measurements are also made of the time required for the primary shock wave to reflect off of the end wall and return to the nearest pressure transducer (turn around time, T_{TA}). Figure 5 shows some of these data for W_R vs W_S and for T_{TA} vs M_s (the primary shock wave Mach number) using the known initial temperature and composition of the driven tube nitrogen gas (N_2). These data are compared with the corresponding predictions from inviscial perfect gas theory as indicated. Our data show consistent trends which differ clearly from the theoretical predictions.

Explicit attention has been focused on the interaction of the reflected shock wave with the disturbed incident gas. As Figure 5 suggests, this interaction is not adequately described by inviscid perfect gas theory. From the measured Mach number of the reflected shock wave, a pressure ratio across the reflected shock wave P_5/P_2 is computed using inviscid flow theory. The result is compared with the measured value of P_5/P_2 to produce a determination of the pressure defect:

$$DPR = \left\{(P_5/P_2)_{meas} - (P_5/P_2)_{calc}\right\} \Big/ (P_5/P_2)_{meas}.$$

Similarly, from the measured pressure ratio, a Mach number for the reflected shock wave is computed using inviscid flow theory to produce:

$$DMR = \left\{(M_R)_{calc} - (M_R)_{meas}\right\} / (M_R)_{calc}.$$

These procedures are checked for consistency by observing the simple linear dependence of DPR on DMR as shown in Figure 5. The pressure defect is examined for Mach member dependence. In Figure 6, the plot of DPR versus M_s shows that increasing Mach numbers are generally associated with increasing pressure defects. At $M_s = 1.27$ and relative Reynolds No. (R_{eo}) of .12 Km/sec (40k ft/sec) the pressure defect is 2.6%. At $M_s = 1.73$ and the same relative Reynolds No., the pressure defect is 34.4%. Similarly, an increase of M_s from 1.42 to 1.61 at (R_{eo}) of roughly .098 units meant an increase in DPR from 11.1% to 24.5%. Generally, for $(R_{eo}) \geq .091$ Km/sec then an increase of M_s by 0.1 means an increase in DPR by 7.5%. In this, the range of values for M_s is $1.2 \geq M_s \geq 1.8$.

Implicit in the above discussion is also our observation of a Reynold's number dependence in the pressure defect measurements. This is shown in Figure 6. Seven experiments have been performed with average Mach number $M_s = 1.32 \leq .03$ and a range of (R_{eo}) where $0.18 \leq (R_{eo}) \leq .44$. One can certainly suggest from these data that, in the cases treated, an increase in Reynold's Number is associated with a decrease in pressure defect.

Projected Accomplishments for the Remainder of the Contract Year

With regard to the experimental set-up, two additional sections of SUMTSHT I will be fabricated in the next few months. The firing section (Section D in Figure 1) will be completed so as to allow for diaphragm rupture under reproducible conditions of pressure. Secondly, a high pressure rectangular test section will be constructed of 5.08 cm (2") nominal height. Supersonic nozzles will be fabricated for use with this test section and provisions will be made for monitoring the flow with high speed pressure transducers. This test section will then be used to obtain high Reynolds number unsteady supersonic flow in a Ludwieg tube configured as shown in Figure 7.

Additional data will be obtained from the experiments on both SUMTSHT I and SUHMITSHT II. The pressure systematics of high Reynold's Number unsteady supersonic flow will be studied using SUMITSHT I in the Ludwieg Tube mode just mentioned. The results will especially be compared with the work reported in Reference 3. Furthermore, the investigations into reflected shock-wave boundary layer interactions will be pursued. By positioning extension pieces at the downstream end of the test section, the effect of increasing the thickness of the boundary layer on our results for measurements of pure defect will be explored. By impregnating the driven tube with dissociating N_2O_4, the coupling of relaxing gas processes with those of the reflected shock-wave turbulent boundary layer interaction will be examined. The forthcoming use of schleren photography in these experiments will also add considerably to our qualitative information concerning the complicated nature of these processes.

Theoretical analyses and research reporting will continue as appropriate. We will continue our studies of modeled flow for thick boundary-layer shock wave interactions. We will continue our studies of turbulence-scale relaxing flow coupling. The recent comparisons of experimental results[4] in turbulent boundary-layer shock tube studies with theoretical predictions[5] will be extended to our case. A paper is in preparation which will report on our reflected shock-wave studies. In addition, we are preparing a paper on NO_2 doped flow in reflected shock-waves for presentation at the San Francisco meeting (January 1972) of the American Physical Society.

References

1. Johnson, J. A., III, "Attenuation of Reflected Shock Waves in Turbulent Shock Tube Flow," Bull. Am. Phys. Soc., 16, 523 (1971)

2. Johnson, J. A., III, "A Proposal of Request for Support of Experimental and Theoretical Research in Nonequilibrium and Unsteady Phenomena in Supersonic Gas Dynamics," Submitted to NASA, June, 1970, Contr. No. 19-005-(003)

3. Johnson, J. A., III, Cagliostro, D., "Starting Phenomena in a Supersonic Tube Wind Tunnel," AIAA J, 9, 101 (1971)

4. (a). Fuehrer, R. G., "Measurements of Incident-Shock Test Time and Reflected Shock Pressure at Fully Turbulent Boundary-Layer Test Conditions," Seventh International Shock Tube Symposium, University of Toronto, Canada, (1970)

   (b) Fiszdon, W., Gomulka, J., Paczynska, H., "Some Unsteady and Non-Linear Effects in the Shock-Wave Reflection Problem," Seventh International Shock Tube Symposium, University of Toronto, Canada, (1970)

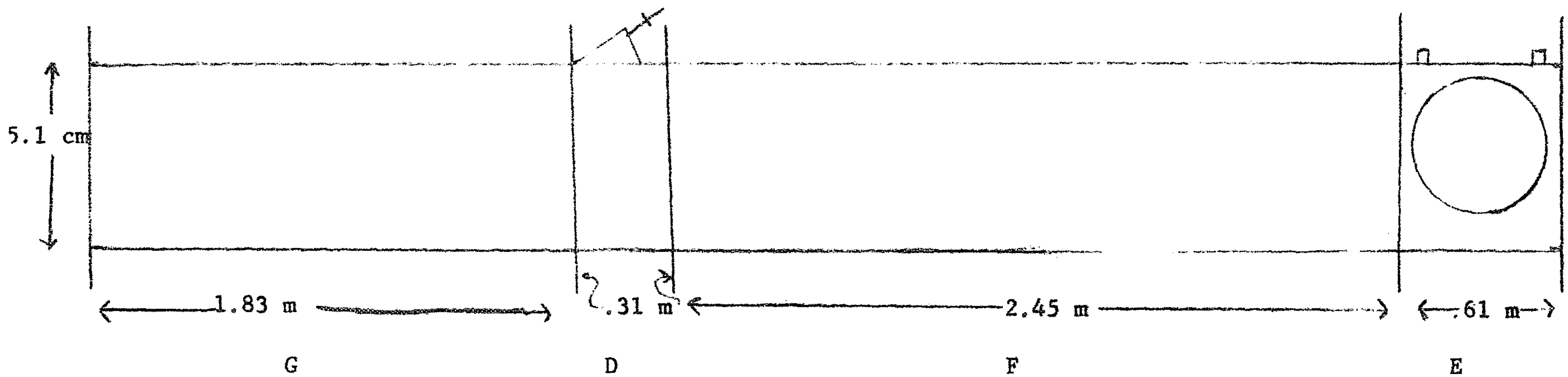


Figure 1. The fourth phase of construction of the Ludwieg tube.

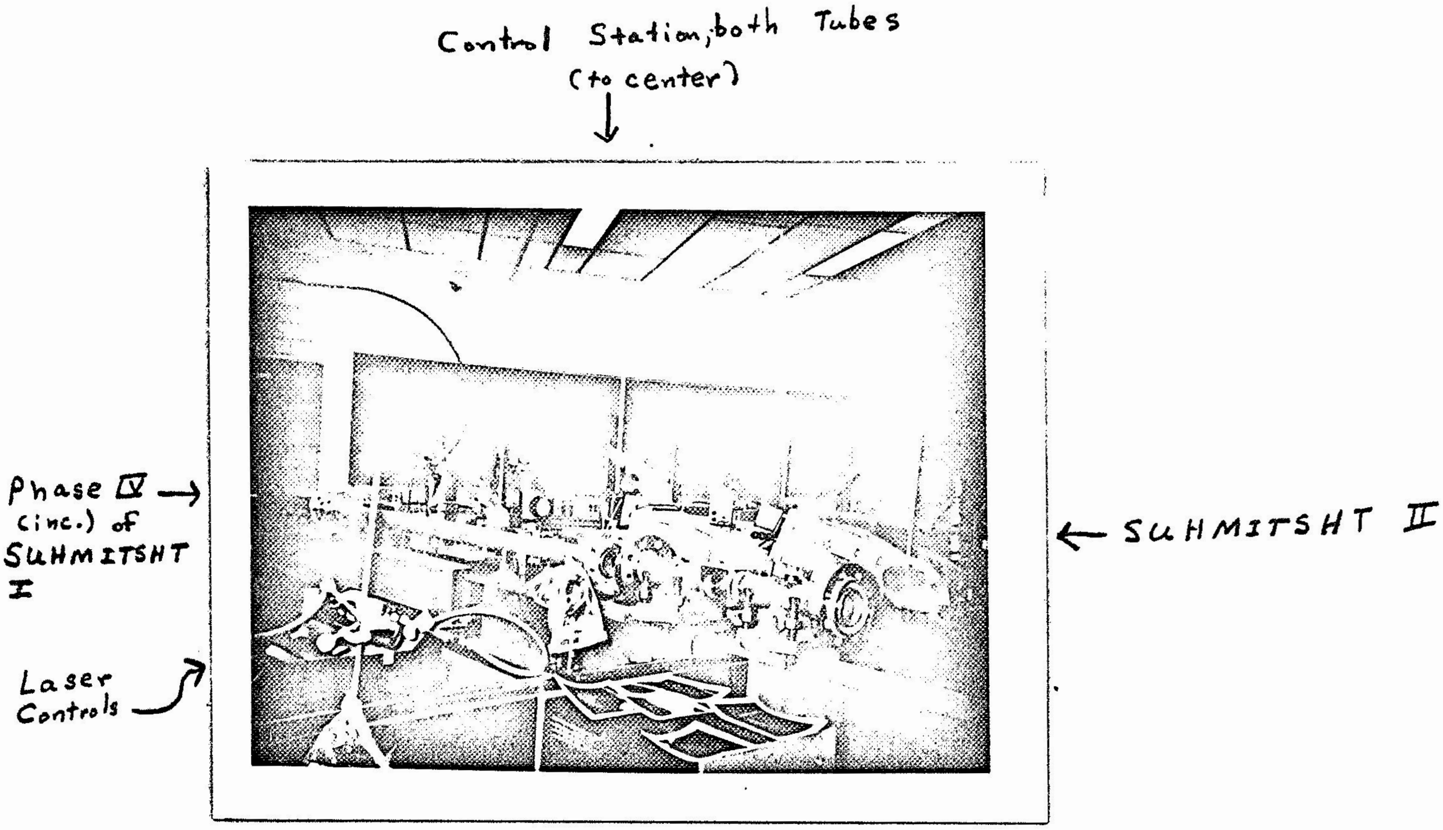


Figure 2. The Gas Dynamics Laboratory.

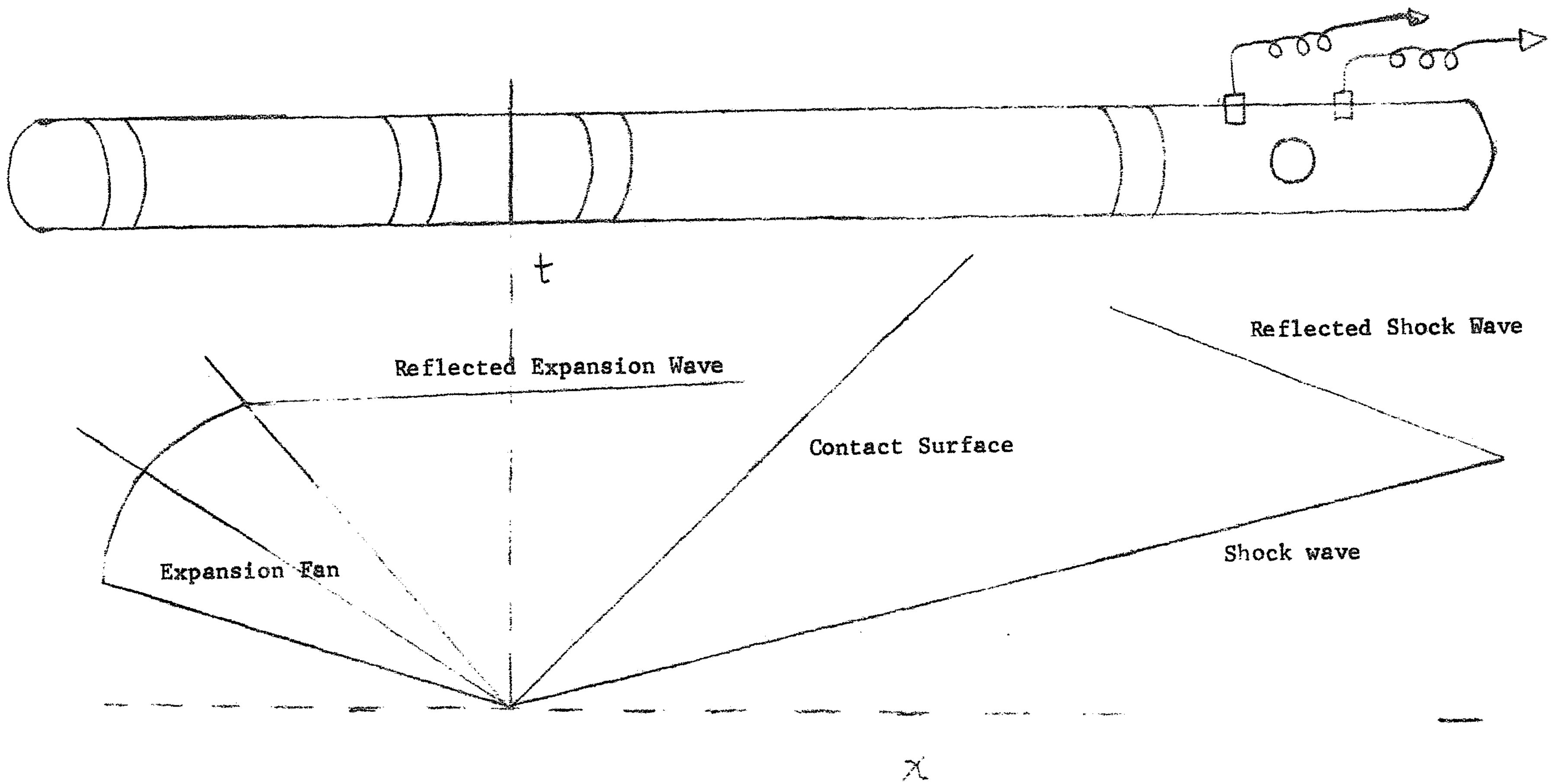
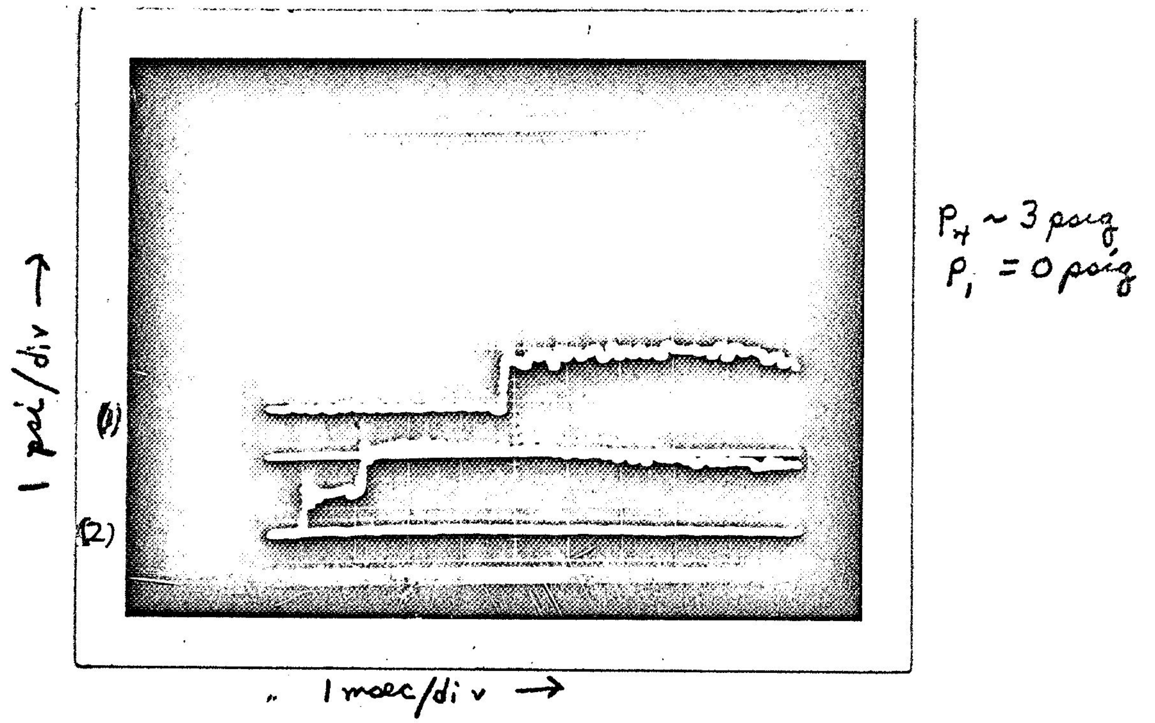


Figure 3. SUMMITSHT II and Flow Diagram for Reflected Shock Wave Studies.



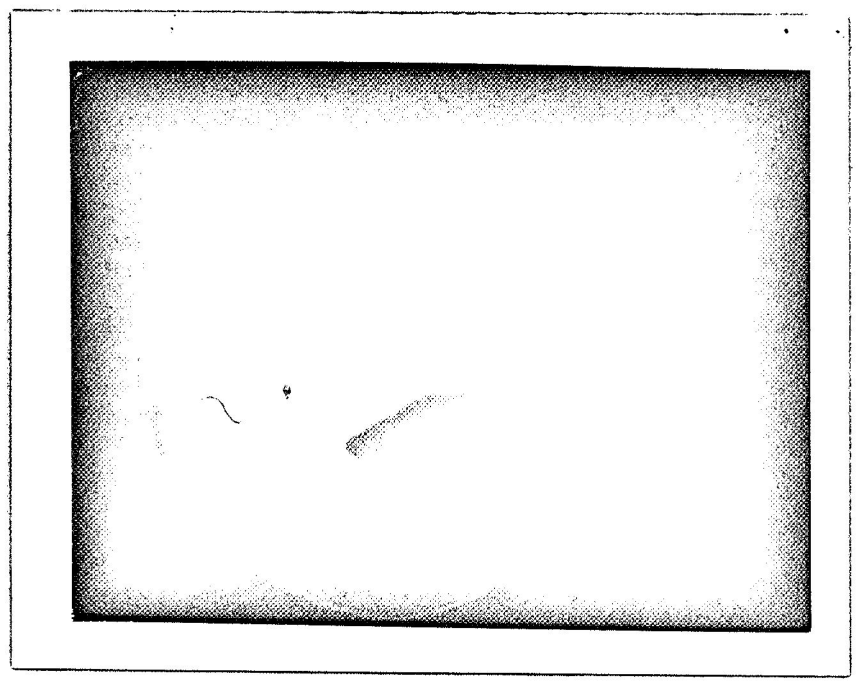


Figure 4. Shakedown Tests: Pressure gauge calibration check and schlieren photograph of soldering iron tip.

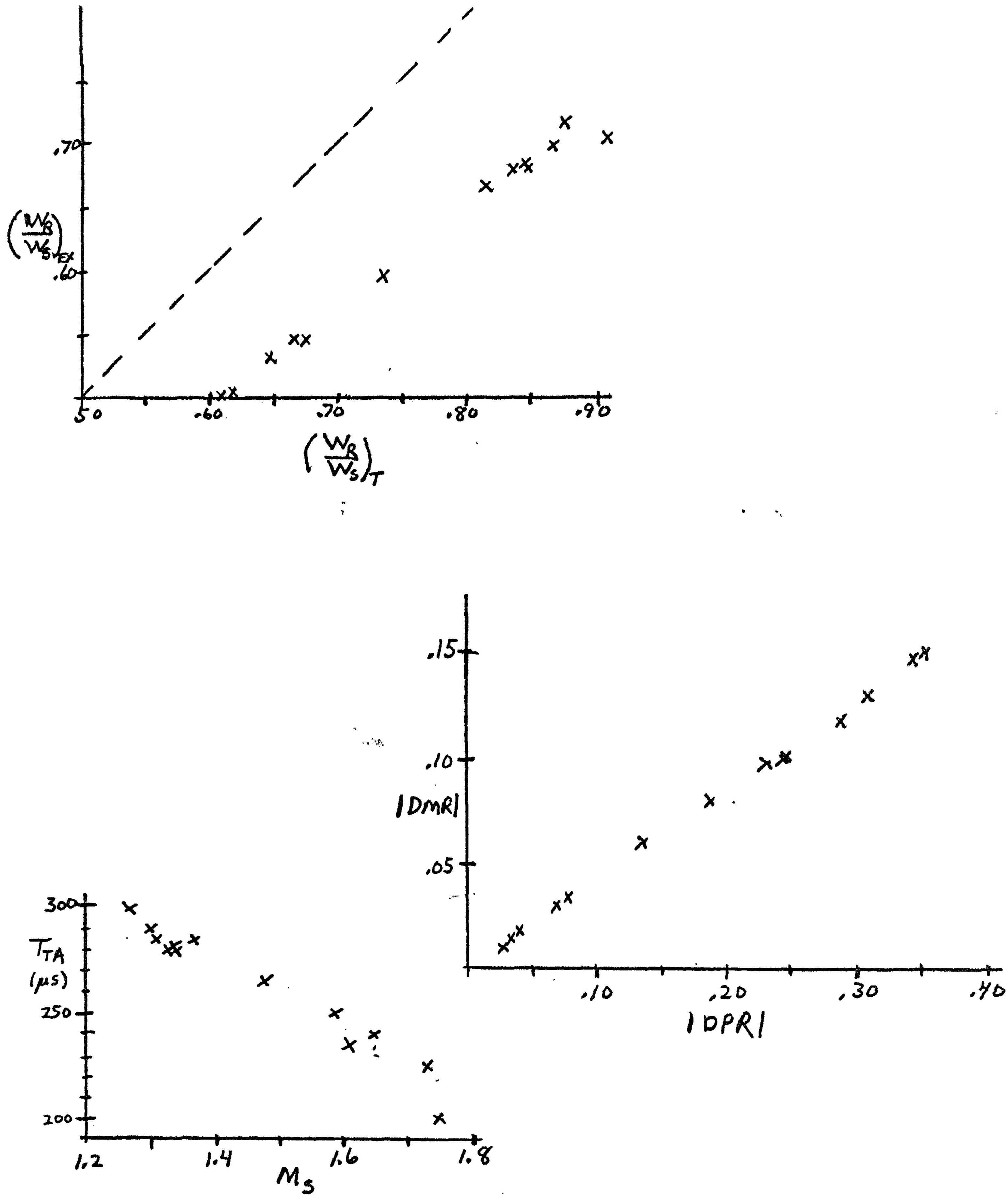


Figure 5. Diagnostics in pressure defect measurements.

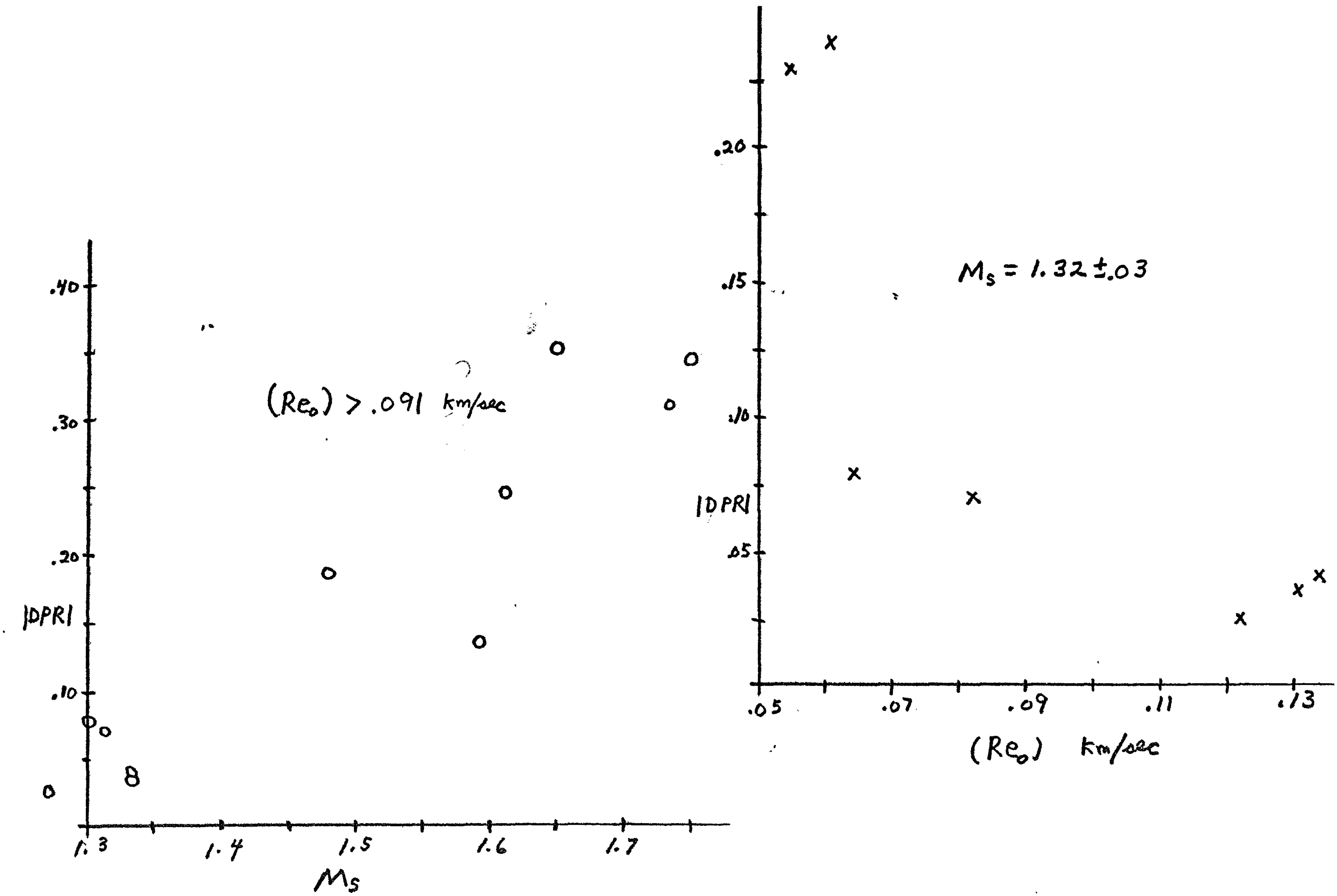


Figure 6. Mach number and Reynold's number sensitivity in the pressure defect measurements.

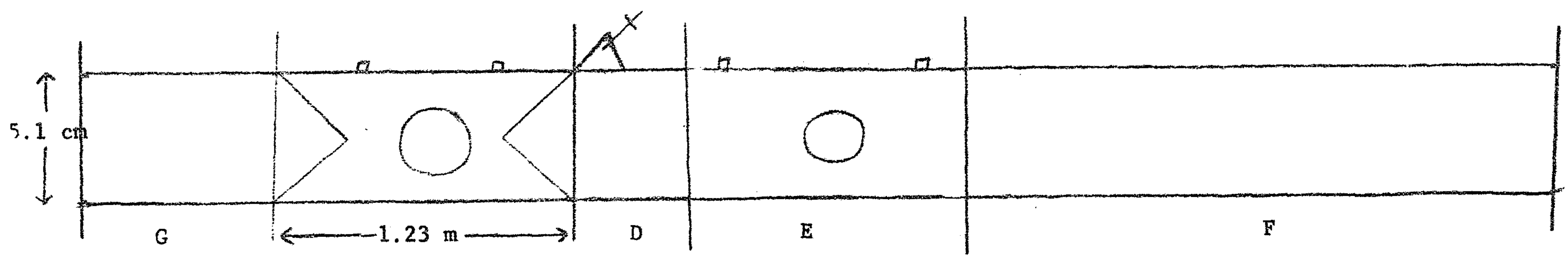


Figure 7. The 2" Special High Pressure Ludwieg Tube. See Fig. 1 for other dimensions.

Abstract Submitted

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Physical Review
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Bulletin Subject Heading in which Paper should be placed
Fluid Dynamics

Attenuation of Reflected Shock Waves in Turbulent Shock Tube Flow.* JOSEPH A. JOHNSON III, Southern Univ., Baton Rouge, La.—A 0.051 m diameter shock tube has been used in studies of shock-wave-turbulent boundary layer interactions in N_2 gas. Primary shock waves of Mach numbers between 1.1 and 2.0 produce turbulent boundary layer flow in the roughened 2.36 m long driven section. Preliminary results from our investigations into the accompanying attenuation of the reflected shock are reported. At a primary shock wave Mach number of 1.39, an increase in P_2 (at .46 atm) by 15% causes a decrease in the attenuation of the reflected shock wave by a factor of 3. At a P_2 of .48 atm, an increase in the Mach number ($M = 1.32$) by 7% causes an increase in the attenuation by 20%. Reflected shock waves for P_2 values between 0.4 atm and 3.0 atm are studied and the effects of varying the turbulent intensity are shown. Comparisons of some of these data with theoretical predictions for fully turbulent pipe flow are discussed.

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Submitted by

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